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*Review Article*

# A Comparative Performance Analysis of Modeling and Simulation Tools for Smart Grid

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***Abstract*** *- A smart grid is a comprehensive system that integrates various components with the power system and communication infrastructure to control it. As the communication infrastructure began to integrate, the potential security risks increased. Unlike the existing IT system, controlling the power system involves physical operations and processes, leading to new risks amplifying even existing risks. However, availability is more important than anything else in the system, so it is necessary to identify possible threats in advance in the smart grid system. The Smart Grid is the need of the hour, which essentially requires testing different scenarios and conditions to meet the realistic and real-time requirements. Therefore, various potential risks need to be analyzed that may help in establishing modelling and simulations to meet the requirements. This paper presents the review and comparative analysis of simulation tools and modelling Plug-ins.*

***Keywords*** *- Smart grid, Simulators, Modeling Tools, Co-simulators, Internet of Things (IoT).*

## 1. Introduction

The direct current (DC) has many drawbacks, and the alternate current (AC) is introduced to overcome these drawbacks. In the early stage of the invention of AC, it was impossible to think about storing it. It was not demand-driven, and there was no hierarchical structure in any phase (Transmission, distribution, generation). [1]. To overcome these challenges, the smart grid emerges as a revolution in the field of grid systems [2]. Smart grid includes IoT technologies (sensors, Radio-frequency identification (RFID) tags), data analytics with artificial intelligence and machine learning for load profiling, forecasting demand, communication technologies, and standards to communicate data to and forth smart meters and generation units and other various technologies from Industry 4.0 [3]. Some of the key characteristics of the smart grid are briefed below: -

### *1.1 Self-healing*

It uses the FLISR (fault location, isolation, and service restoration) technology, minimizes blackout, continuous self-assessment, analyzes, reacts, inspects, and autonomous response to the situation [4].

### *1.2 Flexible*

The electricity is on-demand, pricing is according to peak/non-peak hours, the controlling of all the equipment of home from the smart meter only, the real-time monitoring of electricity consumption and bidding of the price of electricity all these features make the grid flexible [5].

### *1.3 Decentralized Energy Generation*

Now, the energy is generated and stored closer to the consumers utilizing renewable energy sources like wind, hydro and solar. One can also generate electricity on their premises and consume it according to their need, and the excess amount of energy can be sold out to the utility [6].

The paper is organized into five sections: Section II presents smart grid components, network, and architecture, Section III explores the tools for implementing the smart environment, and details various simulators and co-simulators. Section IV presents a comparative performance analysis of some of the simulators based on their performance and efficiency. Section V describes the conclusion of the paper.

## 2. Smart Grid Architecture

The smart grid consists of a smart meter (SM), advanced metering infrastructure (AMI), communication channel, substation, and electric vehicles. The power is generated at the substation and transmitted through the micro-grid to consumers. The network architecture of the smart grid is shown in Fig. 1.

The smart meter controls energy consumption by each socket/equipment through Home Area Network (HAN) [7]. A smart meter identifies the number of appliances working in a home amount of energy consumed at home, controls the electricity consumption at peak/non-peak hours, and sends the consumed amount of electricity to the utility for the billing purpose [8]. The energy consumption notifications emergency messages are sent to the customer through General Packet Radio Service (GPRS) technology. All the equipment/sockets of the home are connected to the smart meter through a home area network such as Zigbee, Ethernet (wired/wireless), and Bluetooth. Once the smart meter holds on to all the data, it sends it to the AMI. The connection of SM and AMI is through Neighbor Area Networks (NAN) topology. NAN is a network of various smart meters and gateways connecting in a tree, star, or mesh network. The devices in HAN and NAN are mostly wireless. All the data from AMI sends to utility servers through Wide Area Network (WAN). WAN uses fibre optics, GSM/LTE/3G/4G, WIMAX, and satellites for communication [9][10]. Here is a list of technologies used in HAN, NAN, and WAN, along with their data rate and coverage rang.

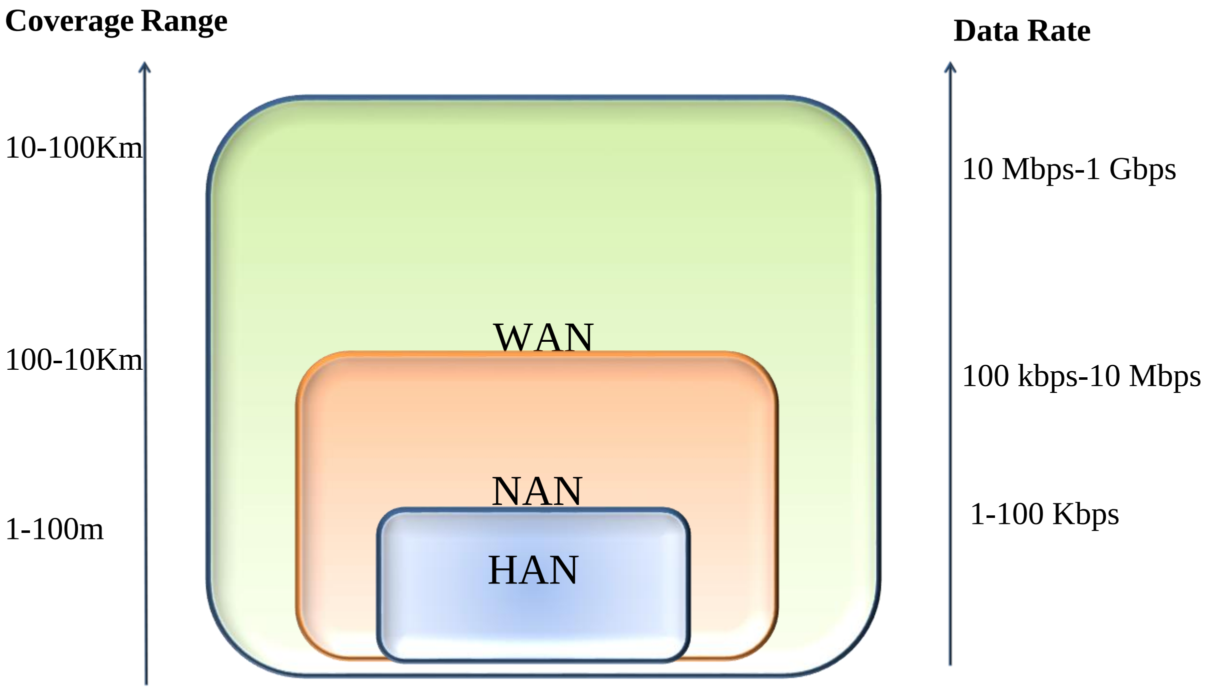



**Fig. 1 Network Architecture**

**Table 1. Technology along with Specifications**

| Sr. No | Technology | Standard/Protocol | Data Rate | Coverage Range | HAN | NAN | WAN |
|---|---|---|---|---|---|---|---|
| 1 | Zig Bee | Zig Bee | 250 Kbps | Up-to 100 m | X | X | - |
| | | ZigBee Pro | 250 Kbps | Up-to 1600m | X | X | - |
| 2 | Bluetooth | 802.15.1 | 721 Kbps | Up-to 100m | X | - | - |
| 3 | Wi-Fi | 802.11.x | 2-600 Mbps | Up-to 100m | X | X | - |
| 4 | Wireless mesh | Various 802.11& 802.15 | Depending on Selected Protocol | Depend on deployment | X | X | - |
| 5 | Cellular | 2G,3G,4G | 14.4Kbps, 2Mbps, 100Mbps | Up-to 50 Km | - | X | X |
| 6 | Satellite | Satellite Internet | 1Mbps | 100-6000km | - | - | X |
| 7 | Ethernet | 802.3 | 10Mbps – 10GBps | Up-to 100m | X | X | - |
| 8 | Coaxial Cable | DOCSIS | 172MBPs | Up-to 28 km | - | X | - |

## 3. Simulation Tools for Smart Grid

The implementation of a smart environment is a complex process. It includes a pool of software and hardware components like- sensors, RFID tags, internet, database, cloud, simulation tools etc. In this paper, some of the simulation and co-simulation tools are discussed.

### *3.1 Need for Simulator*

A simulation is software used for experimental validation of architecture in a real-time environment and hardware in a loop. It acts as a prototype model to check feasibility, remodelling, engineering, performance-enhancing, testing, and training to avoid the real-time hassle. It is used for designing power grids and communication networks. Researchers or industries use simulation tools to test performance, efficiency, and security and reduce the cost of developing or upgrading a system [11]. No doubt, simulators are the predominant evaluation techniques in the field of computer networks. The power network simulator analyzes the operations, price forecasting, power flow, network planning short-circuit, over-voltage, frequency, etc. In contrast, the communication simulator is used for implementing/testing/analyzing new communication protocols and technologies [12].

These are some of the simulation tools which are used widely.

#### *3.1.1 OpenDSS*

It is an open Distributed Simulation Software. Microsoft developed it as an open-source power system simulator for the electric distribution system. It supports the analysis at each phase: General Alternate Current (AC) circuit analyzer, Annual load generation simulation, Wind-power simulation, and Annual power flow simulation [13]. The simulation helps in handling the fault studies. The basic simulator does not have inconvenient communication, but it can be extended by increasing fidelity or co-simulation with the communication simulator [14][15].

#### *3.1.2 MATPOWER*

It is free software introduced to Ray D. Zimmerman, Carlos E. Murillo-Sánchez, and Deqiang Gan of PSERC at Cornell University. It can be modified without any permission. Initially, it was developed for power flow. It has M-files, which have built-in functions and libraries. To use MATPOWER, you must have the MATLAB version and optimization toolbox, and both are available from MathWorks [16].

#### *3.1.3 Network Simulator: NS-2/ NS-3*

The NS-2 was introduced in the market back in 1996 and is composed of C++ lines of code along with OTcl script for better control of the simulation. It is used for academic, research, and industrial purposes [17]. It is an open-source network simulator. It is used for simulating network topologies and communication protocols. It supports both wired and wireless networks. The network animator (NAM) is used as GUI and allows users to play, pause, forward and stop the simulation, but it is not a real-time simulation that is considered a virtual world.[18] The NS-3 is not a replacement for NS-2; it is an extended version. It is written in C++ and some parts in python. It supports both emulation and parallel simulation [19][20]. Since NS-3 was developed in 2010 instead of it, there is a continuous improvement, and new versions are in the market with better performance and improved feature sets [21].

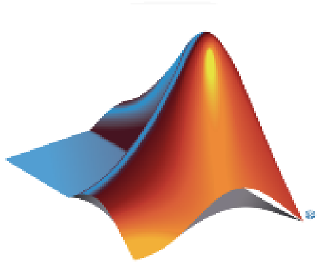
#### *3.1.4 OMNET++*

The OMNET++ stands for Objective Modular Network Testbed in C++ (OMNET++), was developed in 1997 and is still popular among academics and researchers. This test-bed is a communication network simulator and a distributed hardware system with multiprocessors. However, it is open-sourced and can be used for UNIX, Mac OS, and window-based platforms.[22] It consists of simple and unit modules that emphasize the atomicity of the model; so that multiple unit modules can be integrated to form a compound module. These unit modules rest on C++ code, but the integration of this module to form a set-up of network simulators takes place in INED. This tool covers a pool of domains from the peer-to-peer network, ad-hoc network, sensor networks, IPv6 networks, wireless network, storage area networks (SANs), to business process simulator [23][24].

#### *3.1.5 GridLab-D*

It uses end-use models like the consumer model, application and equipment model, retail market model, business and operations simulation tools, SynerGEE's power distribution model, and agent-based simulation methods. It can integrate third-party data management and analysis tools [25][26].

*3.1.6 MATLAB/Simulink*



MATrix LABoratory was developed by MathWorks and came with a visual interface called Simulink. MATLAB has the concept of reusability. That's why there is no need to write code again and again. MATLAB can scale your research. It has provided the interface to interact with other applications. The MATLAB capability includes graphics, Algorithm Development, App Building, Data Analysis, and Parallel Computing [27].

*3.1.7 Global Mobile Information System Simulator (GloMoSiM)*


It is a parallel distributed event simulator used for wireless networks. It is written in C and Parsec, especially used to write parallel programming software.

GloMoSiM supports satellite communication wireless communication having thousands of notes with heterogeneous links. It has an in-build simulation library and a parsec compiler [28][29].

**Table 2. Tools for the Smart Grid**

| S.No | Simulator | Feature/Support | Availability | Major Language | Hardware Required | GUI Support | Operating System | Toolchain/auxiliary tools/Supporting frameworks |
|---|---|---|---|---|---|---|---|---|
| 1 | **OpenDSS** | power system simulator | Open Sourced | Pascal | | Yes | Linux, Windows XP,7 | OpenDSS-G (GUI) |
| 2 | **Network Simulator NS-2, NS-3** | communication network | Open Source | C++, Python | 5GB free space required, min. 256 MB RAM | No | Window XP, Window 7, Vista, Mac OS X, GNU/Linux | the object-oriented dialect of Tcl (OTcl) |
| 3 | **MATLAB/Simulink** | All-purpose simulator | Licensed | MATLAB | Minimum 4GB, Intel or AMD x86-64 process | Yes | Window server 2016 & 2019, window 7, 10,all macOS, and Linux | GUIDE, Simulink, |
| 4 | **Pandapower**[30] | power system simulator | Open-source | Python | | Yes | Window XP and later ones, Linux, Mac OS X, | POWER, pandas |
| 5 | **GridLAB-D** | power system simulator | Open source | C/C++ | Win-32 for Intel-686 system and X-64 for Intel-Itanium system | Yes | Window XP and later ones, Vista, Linux, Mac OS X, | Python, MATLAB |
| 6 | **MATPOWER** | power flow analysis package | Open source | MATLAB | | Yes | Window XP and later ones, Linux, Mac OS X, | MATLAB M-file package |
| 7 | **Global Mobile Information System Simulator (GloMoSiM)** | Communication network simulator | Open Source | Parsec / C | 32-bit/ 64-bit | Limited | Sun SPARC Solaris, Linux, Windows | Parsec Simulation Environment |
| 8 | **OMNET++** | networks simulator | Open source (study & research), Commercial(industrial) | C++/ supports C# and JAVA | 512 MB RAM and 400 MB space on the hard disk. | Yes | Window XP and later ones, Linux, Mac OS X, | Framework or the INET Package |

*Need of Co-Simulation Tools*

The power system simulator and communication network simulator has developed a lot independently. Both are used in the smart grid, so a joint power and communication network simulator is needed to deal with the complex system as a single unit. The co-simulation permits simulation of each unit's power and communication on a single platform. The co-simulator combines multi-functioning simulators based on open-source availability, commercial, application domain, and research topics. Here is an overview of some smart grid co-simulator [32].

**Table 3. Co-simulation Tools for Smart Grid**

| S. No | Paper | Co-Simulation Tool | Power Simulator | Network Simulators | Real-Time | Availability | Interface | Used For |
|---|---|---|---|---|---|---|---|---|
| **1** | [33][34] | **MECSYCO (Multi-agent Environment for Complex SYstems COsimulation)** | FMU simulator (Functional Mock-up Units) | NS-3 | No | Open sourced | Java, C++ | Decentralized multi-simulation, parallel computing. |
| **2** | [35] | **GECO (Global Event-Driven Co-Simulation)** | PSLF | NS-2 simulator | No | Licensed | Java | Fault detection, Transmission, and distribution in the power system using distance relays. |
| **3** | [11] | **PowerNet co-simulation** | Modelica | NS-2 simulator | No | Licensed | UNIX pipes | Helps in Analyzing the Performance, Security, and reliability of different smart grid components. |
| **4** | [36][37] | **Simulink, OPNET** | MATLAB / Simulink | OPNET/ OMNeT ++ | No | Licensed | MATLAB | Insuring the reliability of WAM (wireless area monitoring systems applications). |
| **5** | [38] | **VPNET** | VTB (Virtual Test Bed) | OPNET | No | Licensed | Java Agent Development (JADE) platform | Remotely controlled power electronic devices. |
| **6** | [39] | **Mosaik** | Wind, Solar, photovoltaic, distribution simulator. | OMNeT ++ | Yes | Open Sourced | MATLAB, Python/SimPy | It can integrate multiple simulators and allows communication between all these by using step commands. |
| **7** | [40] | **Michele Garau** | OpenDNS and MATLAB | NS-3 | Yes | Licensed | MATLAB | Supports wireless sensor/network, used for real-time price bidding, particularly used for controlling power generation in the solar photovoltaic system. |
| **8** | [41] | **PiccSIM** | MATLAB /Simulink | NS-2 | Yes | Open Sourced | MATLAB | Controlling the complex systems. |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **9** | [42] | **EPOCHS (Electric Power and Communication Synchronizing Simulator)** | PSCAD/EMTDC or PSLF | NS-2 | No | Licensed | Java | Distributed simulation, Wide-area Monitoring and Control. |
| **10** | [43] | **Cyber-Physical Security Assessment (CPSA)** | MATLAB, PowerWorld | GridSim | Yes | -- | (Windows) | System simulator for cyber security, analysis of the attack impacts. |
| **11** | | **EirGrid** | PowerFactory, MATLAB | NS-3 and mosaik | Yes | Open access | ASN.1, XML, and C/C++ | Used for research on power generation from renewable energies. |
| **12** | [44] | **Virgil** | PowerFactory, Modelica | OMNET++, Ptolemy II | Yes | Open Sourced | C and XML | Implement cyber-security attacks to develop security applications. |

## 4. Computational Results and Performance Analysis

The AODV routing protocol is simulated on various network simulators on the Linux platform.

The number of nodes varied from 500 to 2000. The root node transmits at a regular interval of 2 seconds, and the total run time taken by each node is 500 seconds. The tools and their specifications are in table 4.

Here, the comparison of various network simulators (NS-2, NS-3, GloMoSim, SimPy, OPNET++, JiST) based on performance (CPU utilization, run-time, memory usage, computation time, and scalability) is discussed. The outcome is presented here.

### *4.1 Based on run-time performance*

The various simulation tools are analyzed regarding their run time concerning the network size. It came out that SimPy shows sluggish performance. For example, if we consider a network consisting of 3025 nodes, on an average basis, the SimPy takes 1225 seconds, whereas JiST takes only 86 seconds, which seems to be 14 times faster than SimPy. So, SimPy can't be considered for large-scale network simulation. The JiST is written in Java instead of emerging as a more efficient simulation tool. The reason behind it is the compact architecture of JisT. It seems like the slowness of the java environment is a myth, and the latest Java environment gives a tough competition to simulation tools written in C++. The NS-3 is considerable faster than OMNeT++ and NS-2. But overall, JisT, NS-3, and OMNeT++ are similar scalable.

### 4.2 Based on computational time

When the AODV protocol runs for 500 seconds concerning the increasing order of the nodes, it comes out.

**Table 4. Tools and their specifications**

| **S.no** | **Parameters** | |
|---|---|---|
| **1** | Platform | Linux |
| **2** | Routing Algorithm | AODV |
| **3** | Number of Nodes | 500-2000 |
| **4** | Run Time | 500 sec |
| **5** | Data Size | 512 kb |
| **6** | **Simulators** | **Version** |
| **6.1** | NS-2 | 2.33 |
| **6.2** | NS-3 | 0.1 |
| **6.3** | JIsT | 1.06 |
| **6.4** | SimPy | 1.9.1 |
| **6.5** | OMNeT++ | 3.4b2 |
| **6.6** | GloMoSim | 2.03 |

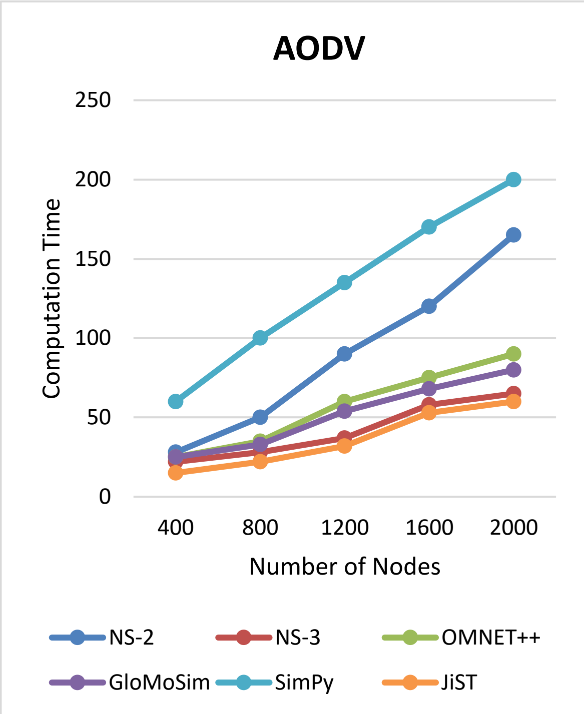



**Fig. 2 Network Size w.r.t Computation Time**

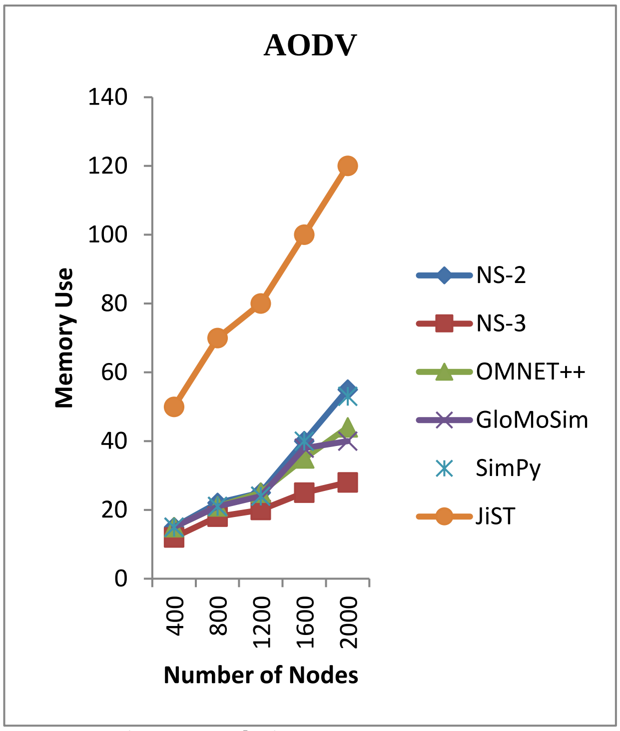



**Fig. 3. Network Size w.r.t Memory Usage**

As the no of nodes starts to increase, the computational time taken by NS-2 gradually increases, which shows it is less scalable than the other three simulators. The footprints of the GloSim and OMNeT++ are quite overlapping. However, JiST And NS-3 became the most scalable simulator, as shown in figure 2.

### *4.3 Based on memory usage*

Here, the AODV protocol is run for 500 seconds with a wide range of nodes (400-2000). The NS-3 uses the least amount of memory resources compared to all six, whereas JiST consumes the highest memory resources. As there is an increase in the number of nodes gradually, the memory consumption of each simulation tool increases. The result of which is a linear graph. Overall, NS-3 is more efficient as compared based on memory usage.

*Based on CPU utilization*

The CPU utilization is calculated based on the number of nodes running parallelly. The CPU utilization (in %) of ns-3 and ns-2 is quite similar, only differs by 5%. When an application is run simultaneously.

- **Performance Analysis and Discussion** By investigating the performance of six network simulation tools, the results show that JiST has been recognized as the fastest as it takes the lowermost computational time and is a scalable simulator. Still, the use of the exhaustive amount of memory limits the use of this simulator. In our relative analysis, NS-3 was the most efficient in global performance. Although in terms of run-time evaluation, JiST is faster. Besides NS-3 and JiST, OPNET++ can be seen as an average simulator with a highly intensive graphical interface, whereas NS-3 and JiST purely rely on source code.

**Table 5. Performance Analysis**

| Performance | NS-2 | NS-3 | OPNET++ | GloMoSim | SimPy | JiST |
|---|---|---|---|---|---|---|
| **Computational time** | 5 | 2 | 4 | 3 | 6 | 1 |
| **Run- Time** | 2 | 5 | 4 | 3 | 1 | 6 |
| **Memory usage** | 4 | 1 | 3 | 2 | 4 | 6 |
| **Scalable** | 2 | 5 | 3 | 4 | 1 | 6 |

Notations:

1-Very Low 2-Low 3-Moderate

4-Higher than moderate 5-High 6-Very High

Table 6 represents the tools, along with their modelling capabilities and plug-ins. This table also indicates the developer information of the respective tools. This table will help determine which tools have supported the randomness w.r.t different scenarios.

**Table 6. Modelling Tools**

| Sr. No | INFORMATION | | SCOPE OF TOOL | PRIMARY PURPOSE OF MODEL | MODEL CONTEXT | MODELLING |
|---|---|---|---|---|---|---|
| 1 | **Tool's Name** | **Developer** | **TSO/DSO level** | **Operational/ Planning** | **Market / Balancing / Network impact** | **Deterministic / Stochastic / Statistical** |
| 2 | LDM-SG | IPE (Institute of Physical Energetics) | DSO | Planning | Network impact | Deterministic / Statistical |
| 3 | eTransport | SINTEF Energy Research | Both | Both | Market / Network impact | LP in the operational module, DP in the investment module, an SDP version is a prototype |
| 4 | MODERNE | University of Strathclyde | DSO | Multi-objective planning | Network Impact - DER integration | Stochastic / Statistical |
| 5 | VPP | TECNALIA | DSO | Operational | Market/balancing | Deterministic |
| 6 | IPSYS | DTU | DSO | Operational | Balancing / Network impact | Deterministic |
| 7 | Flextool | VITO | not relevant | Operational | Market | Statistical |
| 8 | Intelligetor | VITO | Both | Operational | Balancing / Network impact | Deterministic |
| 9 | Power Matcher | TNO | Both | Operational | Balancing / Network impact | Deterministic / Stochastic |
| 10 | Field Simulator | RSE | DSO | Operational | Network impact | Deterministic |
| 11 | MONET | RSE | DSO | Both | Network impact | Deterministic |

## 5. Conclusion

This paper presents a stock of simulators/co-simulators, various modelling tools, and plug-ins to make the environment smart and stable. In prima facie investigation, the paper concludes that the MATLAB/Simulink is a powerful tool/simulator that provides a good interface to implement/simulate the security system for open-loop and close loop systems. It also provides the plug-in for the extension of the different types of systems and scenarios. The performance/comparison graph may be plotted with a single click or command/statement. On the other hand, JiST and NS-3 were the best network simulators in terms of computation time and scalability. In t future, the proposed work will be implemented using MATLAB/Simulink with additional plug-ins for the smart environment like Arduino/Raspberry Pi, etc.

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